

FLEXIBLE HEAT EXCHANGERS

Technical Field

[0001] The invention relates to heat exchangers. The invention has broad application to heat exchangers used to deliver heat to or remove heat from objects as diverse as
5 electrical or electronic devices or equipment, mechanical devices such as transmissions, spindles, compressors and engines, scientific and medical apparatus, living creatures, and the like.

Background

10 [0002] There are numerous situations where it is desirable to remove heat from an object or to deliver heat to an object. Various types of heat exchanger exist. Air cooled heat sinks are structures which take heat from an object and dissipate the heat into ambient air. Such heat sinks typically consist of a finned piece of thermally
15 conductive material having a face which can be placed in thermal contact with an object, such as an electronic component, to be cooled. Some heat sinks are equipped with fans located to flow air past the fins to improve the rate at which heat is dissipated.

[0003] US patent no. 6,549,411 B1 discloses a flexible heat sink that can be attached
20 to a generally flat surface of an object. The heat sink can flex to conform to the surface of the object to achieve improved contact with the object, and hence increase the efficiency of heat transfer between the heat sink and the object. US patent no. 6,367,541 B2 discloses a heat sink that can be attached to multiple electronic chips which have different heights. The heat sink dissipates heat from the chips into
25 ambient air.

[0004] US patent no. 5,368,093 discloses a flexible bag filled with thermal transfer fluid useful for thawing frozen foods. US patent no. 4,910,978 discloses a flexible pack containing a gel. The pack can be cooled and applied to a patient for cold
30 therapy. The pack conforms to surface contours of the patient's body. These devices have limited cooling capacities.

[0005] More sophisticated heat exchangers use a heat exchange fluid, typically a liquid, instead of ambient air to carry heat away from or provide heat to an object to be cooled or heated. US patent no. 5,757,615 discloses a flexible heat exchanger with circulating water as a coolant for cooling a notebook computer. US patent no. 5,643,336 discloses a flexible heating or cooling pad with circulating fluid for therapeutically treating the orbital, frontal, nasal and peri-oral regions of a patient's head. US patent no. 6,551,347 B1 discloses a flexible heat exchange structure having fluid-conducting channels formed between two layers of flexible material for heat/cold and pressure therapy. US patent nos. 6,197,045 B1 and 6,375,674 B1 disclose a flexible medical pad with an adhesive surface for adhering the pad to the skin of a patient. US patent no. 6,030,412 discloses a flexible enveloping member for enveloping a head, neck, and upper back of a mammal for cooling the brain of the mammal suffering a brain injury. All of these heat exchangers require heat to pass through a layer of some flexible material such as rubber, or a flexible plastic such as polyurethane. In addition, heat is exchanged between the surface of the flexible material and a circulating fluid. Water is the most commonly used circulating fluid.

[0006] Rubber and flexible plastics are poor conductors of heat. To provide a high heat transfer efficiency in a flexible heat exchanger in which heat is transferred across a layer of rubber or plastic the layer must be very thin. This makes such heat exchangers prone to damage. In addition, water is a poor heat conductor. Heat exchange between the flexible material and water is largely dependent on convection. Water flowing over a relatively flat surface will not result in efficient heat exchange.

[0007] US patent 3,825,063 discloses a heat exchanger having metal screens of fine mesh with internal plastic barriers that at least partly penetrate the screens. The screens are stacked to provide transverse heat conduction relative to longitudinal flow paths. US Patent No. 4,403,653 discloses a heat transfer panel comprising a woven wire mesh core embedded in a layer of plastic material. The mesh and closure layer extend in the same longitudinal direction. US Patent No. 5,660,917 discloses a sheet

with electrically insulating thermal conductors embedded in it. The apparatus disclosed in those patents is not adapted for warming or cooling living subjects.

5 [0008] There remains a need for heat exchangers capable of providing high heat transfer rates between the heat exchangers and objects that are not flat, are vibrating or are otherwise difficult to interface to. There is a particular need for such heat exchangers which have high ratio of heat-transfer capacity to contact area.

Summary of the Invention

10 [0009] The invention relates to heat exchangers. One aspect of the invention provides flexible heat exchange interfaces. The interfaces have plates of elastomeric material penetrated by substantially rigid thermally conductive members. The thermally conductive members have enlarged pads on at least one side of the plate.

15 [0010] The elastomeric material allows the interfaces to flex while the thermally conductive members are operative to channel heat from a higher-temperature side of the interface to a lower-temperature side of the interface.

20 [0011] Another aspect of the invention provides a flexible heat exchanger comprising a volume having an inlet and an outlet. The volume can receive a heat exchange fluid, for example, water or a water-based coolant. The heat exchanger includes a flexible plate. Substantially rigid thermally conductive members extend through a flexible material of the flexible plate from an outside surface of the flexible plate into the volume.

25 [0012] In preferred embodiments the thermally conductive members each have a thermal conductivity of at least $50 \text{ Wm}^{-1}\text{K}^{-1}$ and preferably at least $100 \text{ Wm}^{-1}\text{K}^{-1}$. The thermally conductive elements may be made of materials such as aluminum, copper, gold, silver, alloys of two or more of aluminum, copper, gold, or silver with one
30 another, alloys of one or more of aluminum, copper, gold, or silver with one or more other metals, carbon, graphite, diamond, or sapphire.

[0013] The thermally conductive members may cover a substantial portion of the outer surface of the flexible heat exchange plate. For example, the thermally conductive members may be exposed in an area of at least 50%, preferably at least 5 70% and, in some embodiments, at least 80% of an area of the flexible heat exchange plate.

[0014] The flexible material of the plate may comprise an elastomer material. The thermally conductive members may be embedded in the elastomer material by any 10 suitable process. The elastomer material may comprise, for example, natural rubber, polyurethane, polypropylene, polyethylene, ethylene-vinyl acetate, polyvinyl chloride, silicone, or a combination of two or more of polyurethane, polypropylene, polyethylene, ethylene-vinyl acetate, polyvinyl chloride, and silicone. In some embodiments the elastomer material has a thermal conductivity not exceeding 5 15 $\text{Wm}^{-1}\text{K}^{-1}$.

[0015] A further aspect of the invention provides a temperature control system comprising a heat exchanger according to the invention, a reservoir containing a heat exchange fluid; a first feed pump connected to feed heat exchange fluid from the 20 reservoir into the heat exchanger and a second feed pump connected to withdraw the heat exchange fluid from the reservoir.

[0016] Further aspects of the invention and features of specific embodiments of the invention are described below. 25

Brief Description of the Drawings

In drawings which illustrate non-limiting embodiments of the invention:

Figures 1A, 1B and 1C are respectively a longitudinal elevational cross-section view; a top plan view and a bottom plan view of a flexible heat exchanger;

Figures 2A, 2B and 2C are respectively a cross-section view; a bottom view; and a top view of the flexible plate of a heat exchanger according to an alternative embodiment of the invention;

Figure 2D is a partial view of the outside surface of a heat exchanger having
5 thermally conductive members arranged in a triangular array;

Figure 2E is a partial view of the outside surface of a heat exchanger having thermally conductive members arranged to provide converging lines of flexible material;

Figure 2F is a view of the outside surface of a heat exchanger having thermally
10 conductive members arranged in a rectangular array oriented at an angle to a long axis of the heat exchanger;

Figures 3A, 3B and 3C are respectively a cross-section view; a bottom view; and a top view of a heat exchanger according to one embodiment of the invention;

Figures 4A through 4L are views of different heat conductors that can be used
15 in heat exchangers according to different embodiments of the invention;

Figures 5A and 5B are respectively an isometric view and a longitudinal elevational section through a pre-curved flexible fluid heat exchanger;

Figures 6A, 6B, 6C and 6D are schematic views of heat exchangers according to the invention being applied to cool various types of apparatus;

Figure 7 is a schematic view of a heat exchanger according to the invention
20 being used to exchange heat with a very hot object;

Figure 8A and 8B are cross-section views of heat exchange interfaces having pads on two sides; and,

Figures 9, 10 and 11 are schematic views of cooling systems according to the
25 invention.

Description

[0017] Throughout the following description, specific details are set forth in order to provide a more thorough understanding of the invention. However, the invention may
30 be practiced without these particulars. In other instances, well known elements have not been shown or described in detail to avoid unnecessarily obscuring the invention.

Accordingly, the specification and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

[0018] Heat exchangers according to the invention have thermally conductive
5 members which can be placed in thermal contact with an object to be heated or cooled. The thermally conductive members pass through a membrane of a flexible material. In some embodiments the membrane is essentially impermeable to a heat exchange fluid that contacts portions of the thermally conductive members that are
10 distal to the object. The membrane permits the heat exchange members to move relative to one another to conform with surface contours of the object. For example, the membrane may permit the members to conform to a convex and/or concave curved surface on the object.

[0019] The thermally conductive members accept heat from a higher-temperature side
15 of the membrane, channel the heat through the membrane, and release the heat to a lower-temperature side of the membrane. The members provide much lower thermal resistance than would be the case if the members were not present.

[0020] In some embodiments, the members have pads on their ends proximate to the
20 object. The pads are dimensioned and distributed in such a manner that the pads cover a large proportion of a heat exchange area of the membrane. In certain embodiments of the invention, pads of a plurality of the thermally conductive members cover at least 50%, preferably at least 70%, and most preferably at least 80% of an area of the outer side of the membrane.

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[0021] An inner side of the membrane may define one side of a channel which carries a heat exchange fluid. Heat exchange fluid may be driven to flow through the channel by way of a suitable pumping system to deliver heat to, or draw heat from, the thermally conductive members.

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[0022] In some embodiments of the invention a plurality of the thermally conductive members have thermally conductive projections, which may comprise, for example, pins, fins, bars, plates or the like that project into the volume of a heat exchanger to form an efficient heat exchange interface with heat exchange fluid in the volume. The projecting pins, fins, bars, plates or the like may or may not be similar in shape or other physical characteristics to the parts of the thermally conductive members that extend through the membrane to form thermal channels through the membrane.

[0023] The thermally conductive members may be made of any suitable thermally conductive materials including thermally conductive metals, for example, aluminum, copper, gold, silver, or alloys of these metals with one another and/or with other metals. The thermally conductive members may also be made of non-metals which have high thermal conductivities such as carbon, suitable grades of graphite, diamond, sapphire or the like. Preferably the thermally conductive members are made from materials having thermal conductivities, k , of at least $50 \text{ Wm}^{-1}\text{K}^{-1}$ and preferably at least $100 \text{ Wm}^{-1}\text{K}^{-1}$.

[0024] Figures 1A through 1C show a heat exchanger 10 according to an embodiment of the invention. Heat exchanger 10 has a heat exchange plate 12 penetrated by a number of thermally conductive members 14. Plate 12 has an outer face 16 and an inner face 18. Heat exchanger 10 has an inside volume 20 and ports 22, 23 by way of which a heat exchange fluid can flow through volume 20. Volume 20 is defined on a front side by plate 12 and on a rear side by a rear wall 24. Side walls 25 extend between plate 12 and rear wall 24. Plate 12, rear wall 24 and side walls 25 are all flexible so that the outer surface 16 of heat exchanger 10 can conform to the local contours of a portion of an object to be heated or cooled.

[0025] Thermally conductive members 14 pass through the material 30 of plate 12. Inside ends 26 of thermally conductive members 14 project into volume 20. Ends 26 preferably project significantly into volume 20. In the embodiment shown in Figure 1, ends 26 are cut away to provide increased surface area for heat transfer with fluid in

volume 20. Each inner end 26 comprises a number of prongs 27. Outer faces 28 of pads 29 on the proximal ends of thermally conductive members 14 can be placed against an object. Pads 29 are separated sufficiently to permit heat exchanger 10 to flex in a desired degree but are preferably closely spaced to maximize the area of outer faces 28 that can be placed against a desired region on an object. For example, in some embodiments, pads 29 are spaced apart from one another by spacings in the range of 0.5 mm to 50 mm. For smaller heat exchangers the spacing between pads 29 is typically at the lower end of this range (i.e. in the range of 0mm to 5mm).

10 [0026] In some embodiments, pads 29 have thicknesses in the range of 0.5mm to 5mm. Preferably, pads 29 have thicknesses in the range of 1mm to 2.5 mm. The sizes and dimensions of pads 29 in the plane of plate 12 may be chosen to suit the application, taking into consideration the contours of the object to be cooled or heated.

15 [0027] Thermally conductive members 14 may have reduced cross sectional areas in their portions toward inner face 18 from pads 29. The cross-sectional area of thermally conductive members 14 at the point that thermally conductive members 14 emerge from material 30 on inner face 18 of plate 12 may, for example, be in the range of 20% to 100%, and in some embodiments is 35% to 65%, of the area of pads 29.

[0028] Thermally conductive members 14 have lengths sufficient to pass through material 30. In preferred embodiments, members 14 project into volume 20. Thermally conductive members 14 may, for example, project into volume 20 for a distance in the range of 0mm to 100mm. For small heat exchangers the projection may be at the lower end of this range (i.e. in the range of 0mm to 20mm). The portions of members 14 which project into volume 20 may also function as supports to maintain a minimum spacing between wall 24 and plate 12. These portions may constitute spacing means for preventing rear wall 24 from collapsing against plate 12.

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[0029] It is not necessary that all thermally conductive members 14 be identical or that all thermally conductive members 14 have equal-sized pads 29 although it is convenient to make heat exchanger 10 with thermally conductive members 14 substantially the same as one another.

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[0030] Material 30 constitutes a flexible membrane through which thermally conductive members 14 extend. In some embodiments, rear wall 24 is made of material 30. Substantially all of heat exchanger 10, except for thermally conductive members 14, may be made of the same material 30. Material 30 is preferably both
10 flexible and elastically stretchable. Material 30 may, for example, comprise natural rubber or any of a variety of suitable flexible polymers such as polyurethane, polypropylene, polyethylene, ethylene-vinyl acetate, polyvinyl chloride, silicone, a combination of these materials or the like. Material 30, or portions of material 30 may optionally be loaded with particles of one or more thermally conductive materials
15 such as metal or graphite. However, since material 30 is not required to play a significant role in conducting heat, material 30 may be a material having a relatively low thermal conductivity (i.e. a thermal conductivity not exceeding $5 \text{ Wm}^{-1}\text{K}^{-1}$) without significantly impairing the function of heat exchanger 10. In some embodiments, material 30 has a hardness in the range of 10 to 80 on the Shore A
20 hardness scale.

[0031] Plate 12 may be fabricated using any suitable process. For example, plate 12 may be made by making holes in a sheet of material 30 and inserting thermally conductive members 14 through the holes. The holes may initially have dimensions
25 smaller than corresponding dimensions of thermally conductive members 14 so that material 30 seals around thermally conductive members 14 sufficiently to prevent any significant loss of heat exchange fluid from volume 20. Additionally, or in the alternative, a sealant, such as a suitable glue, may be provided to enhance the seal between thermally conductive members 14 and material 30. Plate 12 may also be
30 made by a suitable plastic manufacturing process such as thermal injection molding,

reaction injection molding, compression molding, vacuum forming or casting. In this case, thermally conductive members 14 may be molded into plate 12.

[0032] The thickness of material 30 in plate 12 can be selected to provide a desired compromise between flexibility and durability. Since heat exchanger 10 does not rely on material 30 to conduct heat, it is not necessary to make material 30 extremely thin to improve heat conduction. Material 30 may, for example, have a thickness in the range of about 1mm to 20mm. In some currently preferred embodiments of the invention, material 30 has a thickness in the range of 3mm to 7 mm in plate 12.

[0033] Projections of material 30, or some other material, may optionally extend into volume 20. Such projections may be positioned to support wall 24 relative to plate 12, to direct the flow of fluid 65 within volume 20 and/or to induce turbulence at selected locations in the flow of fluid 65 in order to provide enhanced thermal contact between thermally conductive members 14 and heat exchange fluid 65. Such projections may constitute spacing means for preventing rear wall 24 from collapsing against plate 12.

[0034] Thermally conductive members 14 may be arranged in a wide range of patterns. For example, as shown in Figure 1, members 14 may be arranged in rows and columns to form a rectangular array, which could be a square array. In some embodiments, members 14 are arranged in rows or columns which are shifted relative to one another as shown in Figures 2B and 2C. This arrangement creates increased turbulence in fluid flowing through volume 20 and hence increases the efficiency of heat transfer between the inner ends of thermally conductive members 14 and fluid 65. In some embodiments, pads of members 14 are arranged in a rectangular array as illustrated, for example, in Figure 1, while portions of members 14 which project into volume 20 are arranged in rows or columns which are shifted relative to one another as shown in Figures 2B and 2C. In some embodiments, members 14 are arranged in a triangular array, as shown in Figure 2D.

[0035] Flexing of plate 12 may be facilitated by arranging members 14 to provide substantially unbroken lines 31 of material 30 extending generally parallel to one or more axes about which heat exchanger 10 may be flexed. The embodiment shown in Figure 1B shows two sets of lines 31 of material 30 which extend between adjacent rows and columns of members 14. The embodiment illustrated in Figure 2B has one set of parallel lines 31. Lines 31 are not necessarily parallel to one another. For example, Figure 2E illustrates an arrangement of members 14 which facilitates flexing in such a way as to conform to a portion of the surface of a cone. The array of members 14 is not necessarily aligned with any axis of heat exchanger 10. For example, Figure 2F shows the outside face of a heat exchanger wherein thermally conductive members 14 are arranged in a rectangular array oriented at an angle, ϕ , to a long axis of the heat exchanger.

[0036] Figures 2A to 2F and 3A to 3C illustrate heat exchangers in which faces 28 are substantially flush with material 30 on outer face 16. This arrangement facilitates cleaning, as outer face 16 is substantially smooth. Figures 1A to 1C illustrate an embodiment of the invention wherein pads 29 project from material 30 on outer surface 16 of heat exchanger 10. The embodiment illustrated in Figures 1A to 1C can be fabricated, for example, by inserting thermally conductive members 14 through holes formed in a sheet of material 30.

[0037] Thermally conductive members 14 may take any of a wide variety of forms which provide effective means to transfer heat from a higher-temperature side to a lower-temperature side of the membrane. The members preferably provide good thermal interface between the thermally conductive members and the object to be cooled or heated, good thermal channels across membrane material 30, and good thermal interface between the thermally conductive members and the heat exchange fluid in volume 20 of the thermal exchanger.

[0038] Some possible forms for members 14 are illustrated in Figures 4A through 4K. It is understood that these possible forms are illustrated as examples and

modifications to these examples can be made to obtain a much larger list of examples. In addition, features illustrated in these examples can be swapped or combined partially or fully to obtain an even larger list of examples. Figure 4A shows a thermally conductive member **14A** having a square pad **29** and cylindrical pin **32** as means to channel heat through material **30** and to release heat into (or take heat from) the fluid in volume **20** of the heat exchanger. Figure 4B shows a thermally conductive member **14B** having a circular pad **29** instead of a square pad.

[0039] Figure 4C shows a thermally conductive member **14C** wherein both pad **29** and the pin **32** are square in cross-section (like the thermally conductive members of Figures 2A to 2C). Figure 4D shows a thermally conductive member **14D** similar to member **14A** except that pin **32** has a circumferential groove **33** in its part close to pads **29**. Groove **33** receives extra material **30** in an injection molding or casting process to better seal member **14D** to material **30**. Figure 4E shows a thermally conductive member **14E** wherein a tip of pin **32** is tapered to facilitate insertion into a hole in a sheet of material **30**.

[0040] Figure 4F shows a thermally conductive member **14F** having a pair of platelike rectangular conductors **34**. Conductors **34** carry heat through material **30** and provide a mechanism for releasing heat into (or taking heat from) heat exchange fluid in volume **20**. Conductors **34** may be arranged in a V-shape to better transfer heat to fluid flowing past plates **34**. Plate-like conductors could also be arranged in other manners such as being parallel with each other. Thermally conductive member **14F** has the advantage that it can be made by cutting and folding a thermally conductive sheet material.

[0041] Figure 4G shows a thermally conductive element **14G** having a thermal channel portion provided by a tubular pin **36**. Figure 4H shows a thermally conductive member **14H** having multiple pins **38** extending from pads **29**. Pins **38** provide multiple thermal channels extending from the same pad **29** and projecting into volume **30**. Conductive member **14H** advantageously provides increased contact area

between conductive member **14H** and a heat transfer fluid in volume **20**. Figures 4I and 4J show a thermally conductive member **14I** that is designed to reduce the possibility of fluid leaking between material **30** and member **14I**. Member **14I** may be fabricated in two-pieces **14I-1** and **14I-2** that can be assembled together in a manner that provides good thermal contact between pieces **14I-1** and **14I-2**. In the illustrated embodiment, one of the pieces of member **14I** has a pin **39** which is received in a corresponding socket **40** (see Figure 4J) in the other piece. Pin **39** may have an interference fit in socket **40** to keep the two pieces tightly together and to provide good heat transfer between the pieces. A circumferentially extending groove **41** is defined between pieces **14I-1** and **14I-2**. Groove **41** receives material **30**. The faces of pieces **14I-1** and **14I-2** which contact material **30** may be undercut to provide ridges **42** which help to prevent fluid from leaking past member **14I**. The pieces of multi-piece thermally conductive members may be fastened together in other ways which provide thermal contact between the pieces. For example, fastening means such as screws, rivets, or the like may be provided. Figures 4K and 4L show a thermally conductive member **14K** that is similar to member **14I** but is an integral part. Member **14K** is designed to be cramped onto material **30**. Material **30** projects into a groove **43**. The sides of the groove **43** may be cramped together to hold material **30** around the edges of member **14K** as shown in Figure 4L.

[0042] Figures 5A and 5B show a flexible fluid heat exchanger **50** which is normally curved in the absence of applied forces. Heat exchanger **50** may be used to apply heat to or to cool a substantially cylindrical object. Apart from being curved, heat exchanger **50** is similar to heat exchanger **10** of Figures 1A through 1C.

[0043] Heat exchangers according to the invention may be pre-formed so that surface **16** has a concave and/or convex curvature in the absence of applied forces. Figures 5A and 5B show a heat exchanger in which surface **16** has a pre-formed concave curvature.

[0044] Heat exchangers according to the invention may be applied to heating or cooling objects of diverse types. For example, Figure 6A shows a heat exchanger 10 being used to cool an electric motor 52. Pads 29 contact the curved outer surface 53 of motor 52. Figure 6B shows a heat exchanger 10 being applied to cool a compressor 54 having an outer housing 55 which has a profile having compound curvature. Pads 29 contact surface 55. Compressors having compound curves are frequently used in refrigeration and air conditioning systems. Figure 6C and 6D show a heat exchanger 10 being applied to cool an exchange pipe 56. Pads 29 contact an outer cylindrical surface 57 of exhaust pipe 56.

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[0045] Figure 7 illustrates schematically a heat exchanger 58 being used to cool an object 59 having a temperature high enough that it could cause degradation of material 30. Heat exchanger 58 is similar to heat exchanger 10 except that pads 29 are spaced away from material 30, members 14 are longer and a heat shield 60 is provided between pads 29 and material 30. Each of thermally conductive members 14 extends through a thermally insulating sleeve 59A. Sleeves 59A protect material 30 from becoming overheated through contact with members 14. Shield 60 protects material 30 from heat radiated by object 59.

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[0046] Heat exchangers according to the invention may also be used to transfer heat between fluids and/or between solid objects. Figure 8A shows a heat exchanger 61 comprising a membrane of a material 30 penetrated by thermally conductive members 62. Members 62 have pads 29 on both sides of material 30. As shown in figure 8B, pads 29 can optionally comprise fins, pins or other thermally conductive elements disposed to provide improved thermal contact between pad 29 and a surrounding fluid. The heat exchanger 61A illustrated in Figure 8B has pins 32 projecting from each pad 29. Pads 29 are larger in area than the central portions of members 14 which pass through material 30. The edges of the pads press against the membrane to seal any gap between the member and the membrane so that fluid will not leak from one side to the other.

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[0047] A suitable circulation system may be used to circulate a heat exchange fluid through the volume 20 of one or more heat exchangers as described herein. Water has a high specific heat capacity which makes water or water-based coolants good for use as a circulating fluid 65 in cases where fluid 65 can operate at temperatures where
5 such coolants are liquid.

[0048] It is generally desirable to maintain the pressure of fluid in volume 20 approximately equal to the ambient air pressure surrounding heat exchanger 10. If the pressure within volume 20 is significantly smaller than the ambient air pressure then
10 pressure differences across the walls of volume 20 will tend to collapse volume 20. The projected ends 26 of thermally conductive members 14 or other supports provided in heat exchanger 10 may prevent the walls from complete collapse. If the pressure within volume 20 is significantly larger than the ambient air pressure then heat exchanger 10 will tend to balloon.

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[0049] Figure 9 is a schematic view of a cooling system 100 which includes a heat exchanger 10 and a fluid circulating system 63. Circulation system 63 has an insulated reservoir 64 containing a volume of ice 66. System 63 contains a suitable heat exchange fluid 65, which may be liquid water. System 63 delivers fluid 65 to heat
20 exchanger 10 through delivery conduit 67 and returns coolant to reservoir 63 through a return conduit 68.

[0050] A first feed pump 70 upstream from heat exchanger 10 delivers fluid 65 from reservoir 64 to heat exchanger 10. A second feed pump 72 is located downstream
25 from heat exchanger 10. Second feed pump 72 draws fluid 65 from heat exchanger 10 and returns the fluid to reservoir 64. First and second feed pumps 70 and 72 are balanced so that the pressure of fluid 65 within volume 20 of heat exchanger 10 is substantially equal to the ambient air pressure.

30 [0051] One or more bypass valves may be provided to provide better control over fluid pressure within volume 20. In system 100, an adjustable bypass valve 74 is

connected between the output of first feed pump **70** and reservoir **64**. Bypass valve **74** indirectly regulates the pressure within volume **20**. When bypass valve **74** is opened, a larger proportion of fluid **65** is returned to reservoir **64** by way of bypass conduit **75** and the amount of fluid **65** flowing into heat exchanger **10** is reduced. Bypass valve
5 **74** may be pressure-operated.

[0052] System **100** has a second bypass valve **76** connected in parallel with second feed pump **72**. When second bypass valve **76** is open, second feed pump **72** can draw fluid **65** from reservoir **64** by way of conduit **77**. Opening second bypass valve **76**
10 increases pressure at the input of second feed pump **72** and consequently increases the pressure within volume **20**.

[0053] Many variations of system **100** are possible. Although two bypass valves are shown in Figure 9 for maximum flexibility, one bypass valve connected in parallel
15 with either one of pumps **70** or **72** or in parallel with heat exchanger **10** may be sufficient to permit pressure inside heat exchanger **10** to be maintained within a desired range. In addition, depending upon the construction of pumps **70** and **72** and the fluid flow properties of the circuit which includes conduits **67**, **68** and heat
20 exchanger **10** it may be possible to maintain the fluid pressure in volume **20** within the desired range without the need for bypass valves **74** and **76**. Where bypass valves are provided it is not necessary that they be connected directly to reservoir **64** as illustrated. Other connections may be provided which have the result of maintaining pressures upstream and/or downstream from heat exchanger **10** at values which keep the pressure within volume **20** at a desired level while maintaining fluid flow through
25 volume **20**.

[0054] In some cases it may be convenient to provide a single reservoir **64** for providing heat exchange fluid for multiple heat exchangers **10**. In such cases it is best to provide upstream and downstream pumps **70** and **72** for each heat exchanger **10**. In
30 the alternative, suitable manifolds, such as T-connectors, could be provided to allow a

number of heat exchangers **10** to be connected in parallel between a single upstream pump system and a single downstream pump system.

5 [0055] Figure 10 illustrates another fluid circulating system **100A**. In system **100A**, a first flow regulator **78** comprising a restrictor **80** and a bypass valve **82** is provided between first feed pump **70** and heat exchanger **10**. Bypass valve **82** is connected in parallel with restrictor **80**. When fluid **65** is flowing through flow regulator **78** then a pressure drop across flow regulator **78** depends upon the fluid flow rate and upon the degree to which bypass valve **82** is open.

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[0056] System **61A** has a second flow regulator **79** which includes a second flow restrictor **84** and a bypass valve **86**. Bypass valve **86** is connected in parallel with restrictor **84**. In system **100A**, bypass valves **82** and **86** are adjustable. The fluid pressure within volume **20** can be controlled by adjusting one or both of bypass valves
15 **82** and **86**.

[0057] Some alternative embodiments of the invention lack one of flow regulators **78** and **79**. When system **100A** is connected to supply fluid **65** to a plurality of heat exchangers **10** it is preferable to provide for each heat exchanger **10** at least one
20 adjustable flow regulator **78** or **79** located where only fluid going to or from that heat exchanger passes through the flow regulator. This permits the pressure within each heat exchanger **10** to be individually regulated. In the alternative, as described above, suitable manifolds may be provided to split the flow of fluid **65** between a number of heat exchangers **10** connected in parallel.

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[0058] Figure 11 illustrates another fluid circulating system **100B**. In system **100B** the pressure within volume **20** of heat exchanger **10** is controlled by adjusting the rate of operation of one or both of upstream and downstream feed pumps **70** and **72**. In some
30 embodiments of the invention a control system simultaneously increases the rate of operation of feed pump **70** and decreases the rate of operation of feed pump **72** or vice versa. The rate of operation of pumps **70** and **72** may be controlled by adjusting the

rate of rotation of motors which drive the pumps, by adjusting displacements of the pumps, or the like.

5 [0059] In the illustrated embodiment, control is accomplished by operating a power splitter **88** (illustrated schematically by a potentiometer). Power splitter **88** can be operated to increase the speed of a motor driving pump **70** and to decrease the speed of a motor driving pump **72** or vice versa.

10 [0060] Systems **100**, **100A** and **100B** may be automatically controlled using any suitable control system. For example, a controller may be provided to operate bypass valves and/or control pump speeds or displacements by way of suitable actuators (not shown) as necessary to control pressure within volume **20** to stay within a desired range. Those skilled in the art are familiar with suitable controllers. The controller may, for example, comprise a suitably programmed programmable controller or a
15 hardware control circuit. One or more pressure sensors and/or flow sensors (not shown) may be included to provide feedback to the controller.

[0061] Any of cooling systems **100**, **100A** or **100B** may be adapted for warming by replacing ice **66** with a suitable heating element which can be operated to warm fluid
20 **65** in reservoir **64** to a desired temperature. Instead of ice **66**, any of systems **100**, **100A** or **100B** could include a refrigeration system to cool fluid **65**.

[0062] Where a component (e.g. a member, assembly, element, device, circuit, etc.) is referred to above, unless otherwise indicated, reference to that component (including a
25 reference to a "means") should be interpreted as including as equivalents of that component any component which performs the function of the described component (i.e., that is functionally equivalent), including components which are not structurally equivalent to the disclosed structure which performs the function in the illustrated exemplary embodiments of the invention.

[0063] As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. For example:

- 5 • Thermally conductive members **14** may have any suitable shapes and arrangements. Those illustrated herein are but examples.
- Flexible material **30** may have different compositions in different parts of a heat exchanger according to the invention. Different suitable flexible materials **30** may be used for material **30** in different parts of a heat exchanger.
- 10 • A heat exchanger according to the invention is not necessarily rectangular or parallel-sided. A heat exchanger according to the invention could have other shapes. Heat exchangers according to some currently preferred embodiments of the invention are elongated and have fluid inlets and fluid outlets located in areas at opposed ends of a long axis.

 Accordingly, the scope of the invention is to be construed in accordance with the
15 substance defined by the following claims.